

Novel features of J/Ψ dissociation in matter

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We make a detailed study of the effect that the recently predicted modification of the in-medium masses of charmed mesons would have on J/Ψ dissociation on pion and ρ -meson comovers in relativistic heavy ion collisions. We find a substantial dependence of the J/Ψ absorption rates on the density and temperature of the nuclear matter. This suggests that a quantitative analysis of J/Ψ dissociation in nucleus nucleus collisions should include the effects of the modification of meson masses in dense matter.

The modification of hadronic properties in a nuclear medium may be related to the partial restoration of chiral symmetry [1] – an idea which is currently receiving considerable attention. Some experimental evidence for such effects has been discovered recently – e.g., see Ref. [2] for a review.

There is also a great deal of interest in possible signals of Quark-Gluon Plasma (QGP) formation (or precursors to its formation) and J/Ψ suppression is a promising candidate which has recently shown an anomalous result [3,4]. On the other hand, there may be other mechanisms which produce an increase in J/Ψ absorption in a hot, dense medium. We are particularly interested in the rather exciting suggestion, based on the quark-meson coupling (QMC) model [5], that the charmed mesons, D , \bar{D} , D^* and \bar{D}^* , should suffer substantial changes in their properties in a nuclear medium [6]. This might be expected to have a considerable impact on charm production in heavy ion collisions.

In Ref. [6] it was found, for example, that at a density $\rho_B=3\rho_0$ ($\rho_0=0.15 \text{ fm}^{-3}$) the D -meson would feel an attractive scalar potential of about 120 MeV and an attractive vector potential of about 250 MeV. These potentials are comparable to those felt by a K^- -meson [7,8], while the total potential felt by the D is much larger than that for the vector mesons, ρ , ω and ϕ [9]. Within QMC it is expected that the mass of the J/Ψ

should only be changed by a tiny amount in nuclear matter [7,9]. A similar result has also been obtained using QCD sum rules [10].

In the light of these results, it seems that the charmed mesons, together with the K^- , are probably the best candidates to provide us with information on the partial restoration of chiral symmetry. Both open charm production and the dissociation of charmonia in matter may therefore be used as new ways of detecting the modification of particle properties in a nuclear medium.

The suppression of J/Ψ production observed in relativistic heavy ion collisions, from $p+A$ up to central $S+U$ collisions, has been well understood in terms of charmonium absorption in the nuclear medium. However, recent data from $Pb+Pb$ collisions show a considerably stronger J/Ψ suppression [3]. In an attempt to explain this “anomalous” suppression of J/Ψ production, many authors have studied one of two possible mechanisms, namely hadronic processes [11,12,14,15] and QGP formation [16] (see Ref. [4] for a review).

In the hadronic dissociation scenario [11] it is well known that the J/Ψ interacts with pions and ρ -mesons in matter, forming charmed mesons through the reactions, $\pi+J/\Psi \rightarrow D^* + \bar{D}$, $\bar{D}^* + D$ and $\rho+J/\Psi \rightarrow D + \bar{D}$. The absorption of J/Ψ mesons on pions and ρ -mesons has been found to be important (see Refs. [2,12,17] and references therein) in general and absolutely neces-

sary in order to fit the data on J/Ψ production. Furthermore, the absorption on comovers should certainly play a more important role in $S + U$ and $Pb + Pb$ experiments, where hot, high density mesonic matter is expected to be achieved.

J/Ψ dissociation on comovers, combined with the absorption on nucleons, is the main mechanism proposed as an alternative to that of Matsui and Satz [16] – namely the dissociation of the J/Ψ in a QGP. Note that both the hadronic and QGP scenarios predict J/Ψ suppression but no mechanism has yet been found to separate them experimentally.

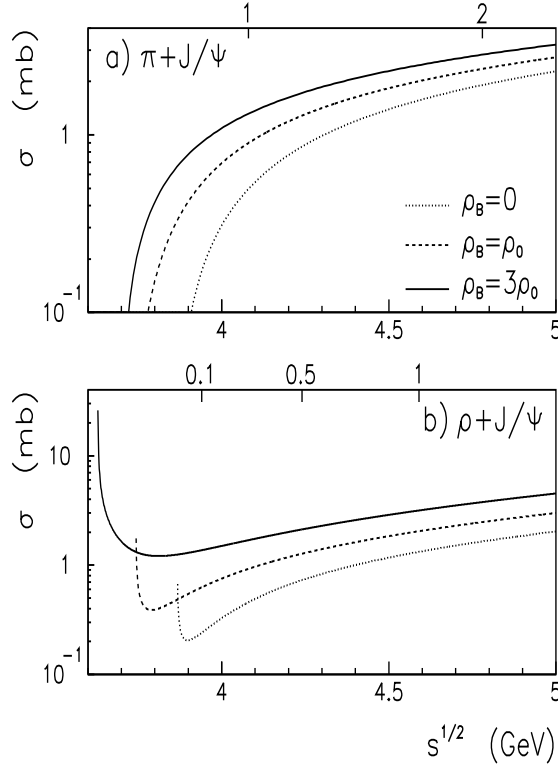


Figure 1. $\pi+J/\Psi$ (a) and $\rho+J/\Psi$ (b) dissociation cross sections as functions of the invariant collision energy, $s^{1/2}$. Results are shown for vacuum (the dotted line), ρ_0 (the dashed line) and $3\rho_0$ (the solid line).

Within the hadronic scenario the crucial point is the required dissociation strength. In par-

ticular, one needs a total cross section for the $\pi, \rho+J/\Psi$ interaction of around $1.5 \div 3$ mb in order to explain the data in heavy ion simulations [2]. Recent calculations [15] of the reactions $\pi+J/\Psi \rightarrow D + \bar{D}^*$, $\bar{D} + D^*$ and $\rho+J/\Psi \rightarrow D + \bar{D}$, based on D exchange, indicate a much lower cross section than this.

The main uncertainty in the discussion of the J/Ψ dissociation on a meson gas is given by the estimates of the $\pi, \rho+J/\Psi$ cross section [15]. The predictions available for the $\pi+J/\Psi$ cross section are given in Refs. [14,15]. Following the meson exchange model of Ref. [15], we show by the dotted line in the Fig. 1 the $\pi+J/\Psi$ (a) and $\rho+J/\Psi$ (b) dissociation cross sections calculated in free space. Moreover, the upper axis of Fig. 1a) indicates the π -meson kinetic energy, T_π , given in the J/Ψ rest frame, which indicates that the pions should be sufficiently hot to be above the DD^* production threshold and to dissociate the J/Ψ -meson. By taking a thermal pion gas with average $T_\pi \simeq 150$ MeV, one might conclude that independent of the $\pi+J/\Psi$ dissociation model used [14,15], the rate of this process is small. However, this situation changes when the in-medium potentials of the charmed mesons are taken into account, because they lower the $\pi+J/\Psi \rightarrow \bar{D}+D^*$ threshold. The upper axis of Fig. 1b) shows the ρ -meson kinetic energy T_ρ in the J/Ψ rest frame. As was discussed in Refs. [2,4,15], the J/Ψ dissociation might proceed on thermal ρ -mesons, because of the low $\rho+J/\Psi \rightarrow \bar{D}+D^*$ reaction threshold.

As far as the meson properties in free space are concerned, the Bethe-Salpeter (BS) and Dyson-Schwinger (DS) approaches have been widely used [18]. The application of BS approach to the description of heavy-light quark systems allows one to describe the D and B meson properties in free space quite well [19]. The DS approach at finite baryon density was used [20] for the calculation of the in-medium properties of ρ , ω and ϕ mesons. The modification of the ρ and ω meson masses resulting from the DS equation is close to the calculations with the quark-meson coupling (QMC) model [5,6,9], while the ϕ -meson mass reduction from Ref. [20] is larger than the QMC result.

Here, we use the quark-meson coupling model [5], which has been successfully applied not only to the problems of nuclear binding and charge densities [21] but also to the study of meson properties in a nuclear medium [6,7,9]. A detailed description of the Lagrangian density and the mean-field equations are given in Refs. [6,7,9,21]. The Dirac equations for the quarks and antiquarks in the D and \bar{D} meson bags (q stands for the light quarks hereafter), neglecting the Coulomb force, are given by [6]:

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q + \frac{1}{2} V_\rho^q \right) \right] \times \begin{pmatrix} \psi_u(x) \\ \psi_{\bar{u}}(x) \end{pmatrix} = 0, \quad (1)$$

$$\left[i\gamma \cdot \partial_x - (m_q - V_\sigma^q) \mp \gamma^0 \left(V_\omega^q - \frac{1}{2} V_\rho^q \right) \right] \times \begin{pmatrix} \psi_d(x) \\ \psi_{\bar{d}}(x) \end{pmatrix} = 0, \quad (2)$$

$$[i\gamma \cdot \partial_x - m_c] \psi_c(x) \text{ (or } \psi_{\bar{c}}(x)) = 0. \quad (3)$$

The mean-field potentials for a bag in symmetric nuclear matter are defined by $V_\sigma^q = g_\sigma^q \sigma$, $V_\omega^q = g_\omega^q \omega$ and $V_\rho^q = g_\rho^q b$, with g_σ^q , g_ω^q and g_ρ^q the corresponding quark and meson-field coupling constants.

The normalized, static solution for the ground state quarks or antiquarks in the meson bags may be written as [7]:

$$\psi_f(x) = N_f e^{-i\epsilon_f t / R_j^*} \psi_f(\mathbf{x}), \quad (j = D, \bar{D}), \quad (4)$$

where $f=u, \bar{u}, d, \bar{d}, c, \bar{c}$ refers to quark flavors, and N_f and $\psi_f(\mathbf{x})$ are the normalization factor and corresponding spin and spatial part of the wave function. The bag radius in medium, R_j^* , which generally depends on the hadron species to which the quarks and antiquarks belong, is determined through the stability condition for the mass of the meson against the variation of the bag radius [6,9,21]. The eigenenergies ϵ_f in Eq. (4) in units of $1/R_j^*$ are given by

$$\begin{pmatrix} \epsilon_u \\ \epsilon_{\bar{u}} \end{pmatrix} = \Omega_q^* \pm R_j^* \left(V_\omega^q + \frac{1}{2} V_\rho^q \right), \quad (5)$$

$$\begin{pmatrix} \epsilon_d \\ \epsilon_{\bar{d}} \end{pmatrix} = \Omega_q^* \pm R_j^* \left(V_\omega^q - \frac{1}{2} V_\rho^q \right), \quad (6)$$

$$\epsilon_c = \epsilon_{\bar{c}} = \Omega_c, \quad (7)$$

where $\Omega_q^* = \sqrt{x_q^2 + (R_j^* m_q^*)^2}$, with $m_q^* = m_q - g_\sigma^q \sigma$ and $\Omega_c = \sqrt{x_c^2 + (R_j^* m_c)^2}$. The bag eigenfrequencies, x_q and x_c , are determined by the usual, linear boundary condition [21].

The D and \bar{D} meson masses in symmetric nuclear matter are given by:

$$m_D^* = \frac{\Omega_q^* + \Omega_c - z_D}{R_D^*} + \frac{4}{3} \pi R_D^{*3} B, \quad (8)$$

$$\left. \frac{\partial m_D^*}{\partial R_D} \right|_{R_D=R_D^*} = 0. \quad (9)$$

In Eq. (8), the z_D parametrize the sum of the center-of-mass and gluon fluctuation effects, and are assumed to be independent of density [21]. The parameters are determined in free space to reproduce their physical masses.

In this study we chose the values $m_q = m_u = m_d = 5$ MeV and $m_c = 1300$ MeV for the current quark masses, and $R_N = 0.8$ fm for the bag radius of the nucleon in free space. Other input parameters and some of the quantities calculated are given in Refs. [6,21]. We stress that while the model has a number of parameters, only three of them, g_σ^q , g_ω^q and g_ρ^q , are adjusted to fit nuclear data – namely the saturation energy and density of symmetric nuclear matter and the bulk symmetry energy. Exactly the same coupling constants, g_σ^q , g_ω^q and g_ρ^q , are used for the light quarks in the mesons as in the nucleon. Through Eqs. (1) – (9) we self-consistently calculate effective masses, m_D^* , and mean field potentials, $V_{\sigma,\omega,\rho}^q$, in symmetric nuclear matter. The scalar and vector potentials felt by the D and \bar{D} mesons are given by [6]:

$$U_s^{D^\pm} \equiv U_s = m_D^* - m_D, \quad (10)$$

$$U_v^{D^\pm} = \mp (\tilde{V}_\omega^q - \frac{1}{2} V_\rho^q), \quad (11)$$

where, $\tilde{V}_\omega^q = 1.4^2 V_\omega^q$, which is assumed to be the same as that for the K^+ and K^- mesons [6,7]. The isovector meson mean field potential, V_ρ^q , is zero in symmetric nuclear matter.

Finally, the D , D^* and ρ -meson potentials used in further calculations are shown in Fig. 2 as a function of the baryon density, in units of $\rho_0 = 0.15$ fm $^{-3}$. Note that these potentials enter not only in

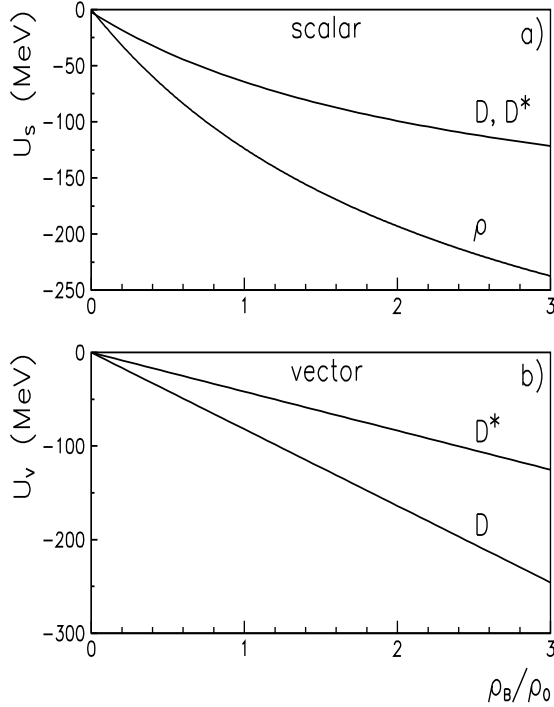


Figure 2. The scalar (a) and vector (b) potentials for the D , D^* and ρ mesons, calculated for nuclear matter as functions of the baryon density, in units of the saturation density of nuclear matter, $\rho_0=0.15 \text{ fm}^{-3}$. Scalar potentials for D and D^* are indistinguishable.

the final state phase space (which becomes larger since the scalar masses are reduced in matter), but also in the reaction amplitude and the initial ρ -meson mass. Furthermore, as observed earlier, the properties of the J/Ψ meson are not significantly altered in medium within QMC.

Note that the total D^- -meson potential is repulsive, while the D^+ potential is attractive, which is analogous to the case for the K^+ and K^- mesons, respectively [6,7]. The threshold reduction is quite large when the nuclear density becomes large for the D^+D^- pairs. Note that a similar situation holds for the K^+ and K^- production and, indeed, enhanced K^- -meson production in heavy ion collisions, associated with the reduction of the production threshold, has been partially confirmed experimentally [2,22].

We first discuss the thermally averaged cross sections, $\langle\sigma v\rangle$, for $\pi+J/\Psi$ and $\rho+J/\Psi$ dissociation in Figs. 3 and 4, when the free masses are used for the charmed mesons and the in-medium potentials are set to zero. They are shown by the dotted lines. These results are needed for comparison with the calculations including the potentials.

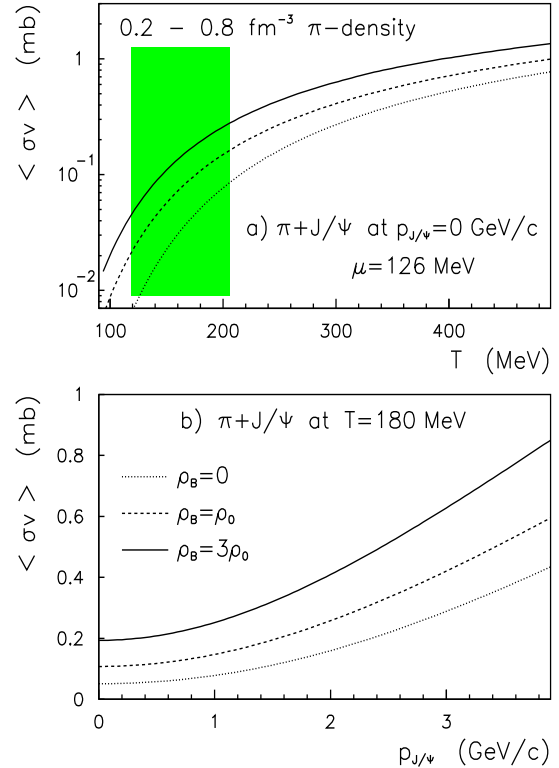


Figure 3. Thermally averaged $\pi+J/\Psi$ absorption cross section as a function of the pion gas temperature, T , and chemical potential, μ , at $p_{J/\Psi}=0$ (a) and as a function of the J/Ψ -momentum at $T=180 \text{ MeV}$ (b). The results are shown using the same notation as in Fig.1. The shadowed area indicates the temperatures expected to be achieved in heavy ion collisions.

Since the pions are almost in thermal equilibrium, their energy spectrum is given by a Bose distribution with temperature, T , and chemi-

cal potential, μ , where we have used the value, $\mu=126$ MeV [23]. The thermally averaged $\pi+J/\Psi$ cross section can be obtained by averaging over the π -spectrum at fixed J/Ψ -momentum. The dotted line in Fig. 3a) shows $\langle\sigma v\rangle$ as a function of the pion gas temperature, T , which was calculated with zero J/Ψ momentum relative to the pion gas.

The shadowed area in Fig. 3a) indicates the temperature range corresponding to the pion densities $0.2 - 0.8 \text{ fm}^{-3}$, which are expected to be achieved in the heavy ion collisions presently under consideration. In vacuum the $\pi+J/\Psi$ dissociation cross section is less than about 0.3 mb. The thermally averaged absorption cross section for temperature, $T=180$ MeV, is shown in Fig. 3b) (the dotted line) as a function of the J/Ψ momentum. The thermally averaged cross section which we find, $\langle\sigma v\rangle$, would be very difficult to detect with the present experimental capabilities.

A similar situation holds for the $\rho+J/\Psi$ dissociation, as illustrated by the dotted line in Fig. 4. Indeed, the J/Ψ absorption on comovers seems to be negligible [15] in comparison with that needed to explain the J/Ψ suppression, provided that we use the vacuum properties of the charmed mesons.

On the other hand, this situation changes dramatically when we consider the effect of the vector and scalar potentials felt by the charmed D , D^* and ρ mesons as calculated by Eqs. (10) and (11). The cross sections calculated for $\pi, \rho+J/\Psi$ collisions with the in-medium potentials are shown in Fig. 1, for densities, ρ_0 (the dashed line) and $3\rho_0$ (the solid line). The dotted line in Fig. 1 indicates the free space cross sections.

Clearly the J/Ψ absorption cross sections are substantially enhanced for both the $\pi+J/\Psi$ and $\rho+J/\Psi$ reactions, not only because of the downward shift of the reaction threshold, but also because of the in-medium effect on the reaction amplitude. Moreover, now the J/Ψ absorption on comovers becomes density dependent – a crucial finding given the situation in actual heavy ion collisions. These effects have never been considered before. The comover absorption cross section is calculated as a function of baryon density for the

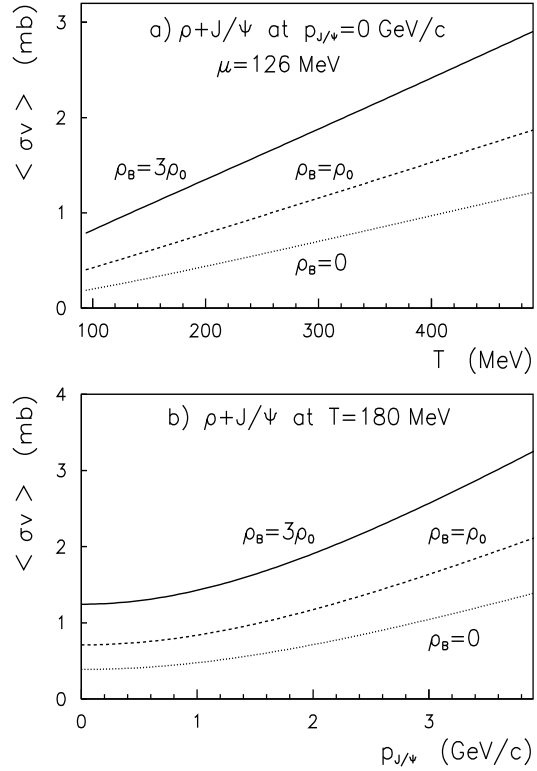


Figure 4. Thermally averaged $\rho+J/\Psi$ absorption cross section as a function of the ρ -meson gas temperature T with $p_{J/\Psi}=0$ (a) and as a function of the J/Ψ -momentum at $T=180$ MeV (b). Notations are similar to Fig. 3.

first time.

The thermally averaged, in-medium $\pi+J/\Psi$ and $\rho+J/\Psi$ absorption cross sections, $\langle\sigma v\rangle$, are shown by the dashed and solid lines in Figs. 3 and 4, respectively. We find that $\langle\sigma v\rangle$ depends very strongly on the nuclear density. Even for $p_{J/\Psi}=0$, with a pion gas temperature of 120 MeV, which is close to the saturation pion density, the thermally averaged J/Ψ absorption cross section on the pion, at $\rho_B=3\rho_0$, is about a factor of 7 larger than that at $\rho_B=0$ (i.e., with no effect of the in-medium modification – see Fig. 3a)).

The thermally averaged $\rho+J/\Psi$ dissociation cross section at $\rho_B=3\rho_0$ becomes larger than 1 mb. Thus, the J/Ψ absorption on ρ -mesons should be appreciable, even though the ρ -meson

density is expected to be small in heavy ion collisions. We note that dynamical calculations [2] suggest that the ρ -density should be around half of the pion density in $Pb+Pb$ collisions.

In order to compare our results with the NA38/NA50 data [3,24] on J/Ψ suppression in $Pb+Pb$ collisions, we have adopted the heavy ion model proposed in Ref. [12] with the E_T model from Ref. [13]. We introduce the absorption cross section on comovers as function of the density of comovers, while the nuclear absorption cross section is taken as 4.5 mb [13]. Our calculations are shown in Fig. 5. The dashed line in Fig. 5 shows the calculations with the phenomenological constant cross section for J/Ψ absorption on comovers $\langle\sigma v\rangle\simeq 1$ mb and is identical to the results given in Ref. [13]. The solid line in Fig. 5 shows the calculations with the density dependent cross section $\langle\sigma v\rangle$ for J/Ψ absorption on comovers calculated in this work. Both curves clearly reproduce the data [3] quite well, including most recent results from NA50 on the ratio of J/Ψ over Drell-Yan cross sections, as a function of the transverse energy up to $E_T=100$ GeV. It is important to note that if one neglected the in-medium modification of the J/Ψ absorption cross section the large cross section $\langle\sigma v\rangle\simeq 1$ mb cannot be justified by microscopic theoretical calculations and thus the NA50 data [3,24] cannot be described.

Furthermore, we notice that our calculations with in-medium modified absorption provide a significant improvement in the understanding of the data [3] compared to the models quoted by NA50 [24]. The basic difference between our results and those quoted by NA50 [24] is that in previous heavy ion calculations [2,4,12] the cross section for J/Ψ absorption on comovers was taken as a free parameter to be adjusted to the data [3,24] and was never motivated theoretically.

To summarize, we have studied J/Ψ dissociation in a gas of π and ρ mesons, taking into account for the first time the density dependence of the scalar and vector potentials which the mesons feel in nuclear matter. We found a substantial density dependence of the J/Ψ absorption rate as a result of the changes in the properties of the charmed mesons in-medium. This aspect has never been considered before when analyzing J/Ψ

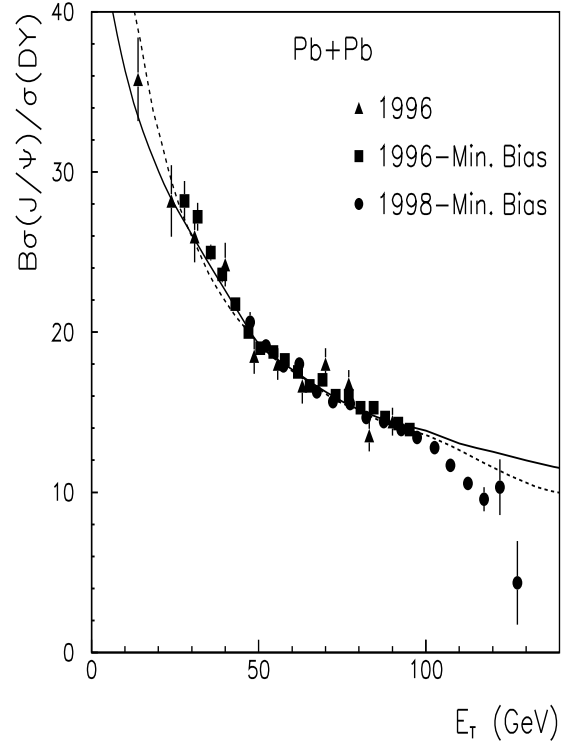


Figure 5. The ratio of the J/Ψ over Drell-Yan cross sections from $Pb+Pb$ collisions as function of the transverse energy E_T . Data are from Ref. [3,24]. The solid line shows our calculations with the density dependent cross section for J/Ψ absorption on comovers. The dashed line indicates the calculations with phenomenological cross section $\langle\sigma v\rangle\simeq 1$ mb [13]. For both calculations the nuclear absorption cross section was taken as 4.5 mb.

production in heavy ion collisions.

Moreover, when we introduce the density dependent cross section on comovers into a heavy ion calculation and compare our results with most recent NA50 data [3,24], our calculations indicate very good agreement with the NA50 data up to transverse energy of order 100 GeV.

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REFERENCES

1. G.E. Brown and M. Rho, Phys. Rev. Lett. 66 (1991) 2720; T. Hatsuda and S.H. Lee, Phys. Rev. C 46 (1992) 34.
2. W. Cassing and E. Bratkovskaya, Phys. Rep. 308 (1999) 65.
3. Quark Matter '97, Nucl. Phys. A 638 (1998); M. C. Abreu et al. (NA50 Collaboration), Phys. Lett. B 410 (1997) 337; Phys. Lett. B 450 (1999) 456.
4. R. Vogt, Phys. Rep. 310 (1999) 197.
5. P.A.M. Guichon, Phys. Lett. B 200 (1989) 235.
6. K. Tsushima, D.H. Lu, A.W. Thomas, K. Saito and R.H. Landau, Phys. Rev. C 59 (1999) 2824; A. Sibirtsev, K. Tsushima and A.W. Thomas, Eur. Phys. J. A 6 (1999) 351.
7. K. Tsushima, K. Saito, A.W. Thomas and S.W. Wright, Phys. Lett. B 429 (1998) 239; *ibid.* B 436 (1998), 453.
8. T. Waas and W. Weise, Nucl. Phys. A 625 (1997) 287; T. Waas, N. Kaiser and W. Weise, Phys. Lett. B 379 (1996) 34; A. Sibirtsev and W. Cassing, Nucl. Phys. A 641 (1998) 476.
9. K. Saito and A.W. Thomas, Phys. Rev. C 51 (1995) 2757; K. Saito, K. Tsushima and A.W. Thomas, Phys. Rev. C 55 (1997) 2637; K. Tsushima, D.H. Lu, A.W. Thomas and K. Saito, Phys. Lett. B 443 (1998) 26.
10. F. Klingl et al., Phys. Rev. Lett. 82 (1999) 3396; A. Hayashigaki, Prog. Theor. Phys. 101 (1999) 923.
11. S.J. Brodsky and A.H. Mueller, Phys. Lett. B 206 (1988) 685; S. Gavin, M. Gyulassy and A. Jackson, Phys. Lett. B 207 (1988) 257; R. Vogt, M. Prakash, P. Koch and T.H. Hansson, Phys. Lett. B 207 (1988) 264; J.-P. Blaizot and J.-Y. Ollitrault, Phys. Rev. D 39 (1989) 232; C.-Y. Wong, E.S. Swanson and T. Barnes, hep-ph/9912431; nucl-th/0002034.
12. N. Armesto and A. Capella, J. Phys. G 23, 1969 (1997); Phys. Lett. B 430 (1998) 23; N. Armesto, A. Capella and E.G. Ferreira, Phys. Rev. C 59 (1999) 395.
13. A. Capella, E.G. Ferreira and A.B. Kaidalov, hep-ph/0002300.
14. D. Kharzeev and H. Satz, Phys. Lett. B 334 (1994) 155; K. Martins, D. Blaschke and E. Quack, Phys. Rev. C 51 (1995) 2723; D. Kharzeev, H. Satz, A. Syamtomov and G. Zinovev, Phys. Lett. B 389 (1996) 595.
15. S.G. Matinyan and B. Müller, Phys. Rev. C 58 (1998) 2994; B. Müller, Nucl. Phys. A 661 (1999) 272.
16. T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416.
17. S. Gavin and R. Vogt, Nucl. Phys. B 345 (1990) 104; S. Gavin, H. Satz, R.L. Thews and R. Vogt, Z. Phys. C 61 (1994) 351.
18. V.A. Miransky, *Dynamical Symmetry Breaking in Quantum Field Theories*, World Scientific Publishing Co., (1993).
19. Yu.L. Kalinovsky and C. Weiss, Z. Phys. C 63 (1994) 275.
20. D. Blaschke and C.D. Roberts, Nucl. Phys. A 642 (1998) 197.
21. P.A.M. Guichon, K. Saito, E. Rodionov and A.W. Thomas, Nucl. Phys. A 601 (1996) 349; K. Saito, K. Tsushima and A.W. Thomas, Nucl. Phys. A 609 (1996) 339.
22. F. Laue et al., Phys. Rev. Lett. 82 (1999) 1640; A. Schroter et al., Z. Phys. A 350 (1994) 101; J.L. Ritman et al., Z. Phys. A 352 (1995) 355; R. Barth et al., Phys. Rev. Lett. 78 (1997) 4007; Y. Shin et al., Phys. Rev. Lett. 81 (1998) 1576; G.Q. Li, C.M. Ko and X.S. Fang, Phys. Lett. B 329 (1994) 149; W. Cassing, E.L. Bratkovskaya, U. Mosel, S. Teis and A. Sibirtsev, Nucl. Phys. A 614 (1997) 415; G.Q. Li, C.M. Ko and G.E. Brown, Phys. Lett. B 381 (1996) 17.
23. K. Kataja and P.V. Ruuskanen, Phys. Lett. B 243 (1990) 181.
24. M. C. Abreu et al. (NA50 Collaboration), Phys. Lett. B 477 (2000) 28.